PRECISION MEASUREMENTS OF NUCLIDE MASSES IN ION TRAPS

(projects in which the Laboratory of Physics of Exotic Nuclei is involved)

One of the main quantities characterizing the properties of any quantum-mechanical system is mass, that is, the total binding energy of this system. Throughout the history of the development of physics of the microworld, mass spectrometry has occupied a prominent place in an effort to achieve maximum accuracy and, thus, to reach new frontiers of fundamental physics. Currently, Penning ion traps, in which one ion is held by magnetic and electric fields in a small volume in a state of almost rest, have the properties of the highest accuracy, reliability and unprecedented sensitivity (at the level of detection of one particle). In terms of accuracy, such traps have already surpassed by many orders of magnitude measurements in storage rings of relativistic particles, which until recently were the most accurate in the nuclear and atomic physics of radioactive nuclides. There are no more than ten such research traps in the world, of which five operate in Europe, and the scientists of Laboratory of the Physics of Exotic Nuclei of the "Kurchatov Institute" - PNPI participate in the operation of each of the European installations.

SHIPTRAP project

The SHIPTRAP ion trap is based on the UNILAC linear accelerator at GSI / FAIR (Darmstadt, Germany). The SHIP speed selector serves as a pre-separator, separating the products of the reaction "fusion + evaporation". The main areas of research are:

- **Superheavy elements.** Measurement of the masses of transuranic and, above all, superheavy elements of D. Mendeleev's table is the main task of the SHIPTRAP , the only system in the world capable of doing this. For several years of work, it was possible to measure the masses of nine nuclides of elements No (Z = 102), Lr (Z = 103), Rf (Z = 104), Db (Z=105) with a relative accuracy of 10^{-8}, which made it possible to determine from alpha decay chains the masses of about 30 more nuclides of superheavy elements up to Ds (Z = 110). The resulting mass landscape led to the conclusion about the presence of two small islands of stability near nuclides with neutron numbers N = 152 and N = 162, located on the approaches to the supposed large island of stability of the Superheavies (see PNPI-activities 2007-2012).

- **Double electron capture.** Search for nuclides in which the resonance conditions in double electron capture are fulfilled, arising when the difference between the masses of the parent and daughter atoms are equal. If this condition is met, the neutrinoless process will be resonantly enhanced and can be identified. Its presence means violation of the lepton charge conservation law and the presence of the Majorana type of neutrino. Of the nineteen pairs of nuclides for which the mass differences were measured with high accuracy, only the pairs ^{152}Gd -^{152}Sm and ^{190}Pt -^{190}Os have a real chance of demonstrating the presence of a neutrinoless decay in a long-term large-scale experiment (see PNPI-activities 2007-2012.)

- **Relativistic effect in QED.** Accurate measurement of the ^{48}Ca mass to a value of $4x10^{-10}$ made it possible, along with the measurement of the Larmor frequency, to determine the g-factor of an electron in the lithium-like ion of this nuclide and, by comparing this value with the ^{40}Ca nuclide, to investigate the isotope effect, as a consequence, the QED properties of the multielectron systems associated with a relativistic effect in the presence of a magnetic field (see PNPI-activities, 2013-2018, p.256).

- **Towards measuring neutrino mass.** The total energy of beta transformation (difference in atomic masses) is the main parameter used to determine the neutrino mass in studies of discharge spectra (atomic or electronic). Nuclides with the smallest known decay energies were selected for research on SHIPTRAP: ^{187}Re in the beta decay channel and ^{163}Ho in the capture channel. The obtained values, respectively, Qβ = 2492 ± 32 eV and QEC = 2 833 ± 34 eV (see PNPI activities 2013-2018, pp. 250-255) are the most reliable and open the way for the use of cryogenic microcalorimetry in the neutrino program (see the ECHo project below). Determining the neutrino mass at a level <1 eV requires similar accuracy in determining the difference of atomic masses. This challenge is addressed to the PENTATRAP installation (see below).

ISOLTRAP and JYFLTRAP projects.

ISOLTRAP. The ISOLTRAP is installed after the ISOLDE mass separator at CERN (Geneva). Joint work is devoted to the precision measurement of the mass differences of ^{194}Hg - ^{194}Au, ^{202}Pb - ^{202}Tl, and ^{131}Cs - ^{131}Xe for the possibility of using them in determining the neutrino mass and studying beta transitions with very low decay energies for investigation of the features of the weak interactions in these decays. (see Eur. Phys. J. A (2017) **53**: 153. and Hyperfine Interact. **240** (2019) no. 1, 61).

JYFLTRAP. On this trap in the cyclotron laboratory of Jyvaskyla University (Finland), the ^{102}Pd - ^{102}Ru mass difference was measured, which confirmed the SHIPTRAP measurements, which significantly differ from the decay spectroscopy data, and, thereby, showed the reliability of measurements using traps (see International Journal of Mass Spectrometry **435** (2019) 204-208).

PENTATRAP project.

The system, started in 2018 at the M. Planck Institute for Nuclear Physics in Heidelberg (Germany) with the participation of the Laboratory of the Physics of Exotic Nuclei of PNPI, consists of five Penning ion traps, allowing the processes of measuring the desired nuclide to be tied to the same time with the calibrating ion. This significantly suppresses the systematic uncertainty, which made it possible to determine the total relative measurement error of the nuclide mass to a record value of 10^{-11} (see Phys. Rev. Lett. **124** (2020) 113001-6).

The project currently covers the following issues:

- ***Total energy release of "neutrino" nuclides.*** Measurements of the total energy release (mass difference) of the parent nuclides ^{187}Re and ^{163}Ho with an accuracy of 1 eV to determine the mass of antineutrino and neutrino, respectively. For ^{187}Re, such measurements have already been performed with an accuracy of 3 eV. Long-term measurements of ^{163}Ho have already started.

- ***New phenomenon - atomic isomerism.*** When measuring the cyclotron frequency for the $^{187}Re^{29+}$ ion, a long-lived metastable state with an energy of 202 ± 2 eV was found, which lives longer than a day (see Nature **581** (2020) 42-46) and, as shown, arising in as result of the spin of external electron failing into the “spin trap”. The correctness of the interpretation of the phenomenon was confirmed by the discovery of a similar state in the $^{187}Os^{30+}$ ion with an energy of 207 ± 3 eV, which has the same isoelectronic structure. The discovered isomers have a large value of the frequency discharge factor, exceeding this value by many orders of magnitude for all known frequency standards. Therefore, the found isomeric levels, along with other long-lived ionic states that have yet to be discovered, can be regarded as the most accurate frequency meters (reference clocks). The performed experiment lays the foundation for a new direction - long-lived high-energy atomic isomerism.

ECHo project

An electron neutrino mass. The ECHo (Electron Capture in Holmium) project aims to measure the effective mass of an electron neutrino in the atomic discharge spectrum after the capture of an orbital electron by the ^{163}Ho nucleus. This spectrum is measured by cryogenic microcalorimetry at the facility at the Kirchhoff Institute of the University of Heidelberg (Germany), and the total capture energy ^{163}Ho measured by the trap is used to determine the neutrino mass. The program is divided into two stages:

At the first stage, a weak source of holmium is used, about one hundred detection pixels, and the total energy of holmium capture measured at the SHIPTRAP facility. A pilot experiment, carried out in the Modane Alpine underground laboratory, showed the good quality of the installation and made it possible to determine the new limit on the neutrino mass, halving the known so far value of 265 eV (see Eur. Phys. J. **C79** (2019) 1026).

At the second stage, it is planned to use a stronger source ^{163}Ho, more than a thousand pixels of the cryogenic detector, and one to two orders of magnitude more accurate measurement of the capture energy performed at the PENTATRAP facility. It is expected that at this stage it will be possible to obtain a limit on the neutrino rest mass at the level of 1 eV.

- ***Sterile and relic neutrinos***. The further plans of the ECHo project include the identification of sterile neutrinos in the energy range of several keV, the presence of which may be responsible for warm dark matter in the Universe, and the search for nuclides in which the resonance conditions for the detection of relic neutrinos are fulfilled, for example, in ^{157}Tb (see J. Phys. G-Nuclear and Particle Phys. **41**, 2014, 12500)

PITRAP project

In the developed PITRAP project, it is proposed to install an ion trap at the exit of radioactive beams from the internal irradiated target at the PIK reactor, thereby taking advantage of the high neutron flux and unrivaled sensitivity of the trap. The landscape of the neutron-rich region obtained on the basis of mass measurements can be used to determine the path of the astrophysical process of rapid neutron capture (r-process), which is responsible for the formation of elements in nature. The estimates of the expected yields of exotic nuclides in the proposed system show that in experiments it is possible to reach nuclei that fit into the assumed path of the r-process. The draft technical assignment is presented in the form of PNPI Report F-310 (2016) and published (see Atomic Energy, **118** (2015) 419-424. DOI 10.1007 / s10512-015-0017-3).